

Capability Requirements Analysis and Integration
(CRAI)
FY 04 Summary White Paper

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Abstract:

This paper discusses the NASA Capability Requirements Aalysis and Integration (CRAI) process, products, and lessons learned in this effort to turn broad NASA objectives into capability and technology investment strategies. The NASA Office of the Space Architect chartered the CRAI team to identify and assess the capabilities and technologies needed to enable the Exploration Vision. The objective was to determine the priority and level of investment needed in a very wide range of capabilities and technologies based on NASA mission requirements using a structured, open, and data driven strategic analysis process. The CRAI process has developed a methodology to meet this objective as well as methods for the performance of rapid sensitivity analysis of changing mission needs and budget forecasts.

In the course of designing and implementing this process, significant lessons were learned in regard to the effective approaches to accomplishing capability analysis and roadmapping activities. These lessons learned are discussed along with some specific observations and recommendations relevant to the Exploration mission.

Background:

Beginning in FY 03, the Office of the Space Architect initiated an activity with the following objectives: 1) Identification, assessment, prioritization, and recommendations of strategic investment capabilities needed to realize the NASA mission; 2) integration of capabilities across the NASA Enterprises, looking for commonality and leveraging opportunities; 3) implementation of a One NASA analysis approach, with products and teams that purposefully model One NASA values; and 4) creation of a structured, open, strategic analysis process with traceability to NASA missions and objectives.

CRAI defined capabilities as “the ability to accomplish something”. Capabilities fulfill the functional requirements as defined by the Design Reference Missions (DRM’s) and Design Reference Architectures (DRA’s). They are comprised of one or more systems of technologies that work together to form a functional unit and fulfill a specific functional requirement.

The CRAI process was envisioned to occur annually and be linked with the NASA budget formulation cycle. The process was designed to be iterative and to assist in analyzing the impact of changes in the mission plans, architectures, and budgets.

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FY 03 was used to design the process and develop effective methods for accomplishing the work to be done. The FY 03 product was high level and preliminary, with the intent that subsequent years would yield greater detail and be more comprehensive. Even with preliminary results, the CRAI FY 03 capability recommendations were endorsed by the 'President's Commission on Implementation of United States Space Exploration Policy'.

FY 04 was focused specifically on the Exploration mission, with the President's announcement coming as the team initiated the work for that year. The FY 04 CRAI team products included: preliminary assessments of 57 capabilities applicable to the exploration mission, 441 associated technology datasheets, limited capability development roadmaps, initial capability and technology databases, and the development of a strategic analysis process that could result in prioritization and optimization of critical NASA capability investments.

Beginning in FY 05, the CRAI team supported the transition of its products and knowledge base (all well documented) to the newly formed National Capability Roadmap teams, sponsored by the Advanced Planning and Integration Office (APIO), which will report directly to the NASA Strategic Planning Council.

Recommended Capability Assessment Process:

The recommended process starts with DRM's/DRA's and logically flows these to capability assessments and investment recommendations, illustrated as follows:

- ⇒ DRM's/DRA's
 - ⇒ Identification of capability needs and requirements
 - ⇒ Capability assessment that includes the technologies which make up the capability
 - ⇒ Integrated analysis of the capability assessments which results in an investment portfolio, investment recommendations, and integrated development roadmaps
 - ⇒ Iterative feedback of these recommendations to the DRM/DRA designer

This hierarchy establishes capability and technology traceability to mission needs, the ability of each capability and supporting technology to meet requirements, and serves as a reference source for "truth-testing" design assumptions. The process can support analysis based on multiple DRM's/DRA's and does not presuppose that once a DRM/DRA is chosen it must remain static throughout the lifetime of the program.

Design reference missions and architectures:

A DRM is a baseline plan for accomplishing the mission and is the overarching and inclusive definition of what must be done, when it must be completed, and where it must be done. Since there may be many ways to accomplish a mission, multiple DRMs are

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allowable as long as they all can accomplish the mission goals. DRMs are used to define mission requirements, addressing the issues of *what* must be done. DRMs include the flight tests as well as the engineering and scientific precursor flights such as entry tests for heat shields and atmospheric characterization tests.

A DRA is a baseline plan that fully describes the functionality and physical structures or systems and address a specific DRM. As with DRM's, there can be multiple DRA's as long as they satisfy the requirements of a DRM. DRA's are used to define capability requirements that take the form of a functional requirement.

Identification of capability needs and requirements:

Critical to capability assessments are the identification of capability requirements from DRA's. These capability requirements must include metrics in order to determine if there are gaps in current capability state-of-the-art and how severe these gaps may be. Iteration between the mission designers and the capability assessors is needed in order to fully understand and define the needs, assumptions, functional requirements and metrics.

Capability assessment and analysis:

The goal of the capability analysis process is to provide investment recommendations based on a data-driven, open, structured strategic analysis. CRAI planned to apply two approaches, a Portfolio and a Technology analysis method. Both are based on capability and technology data in a common format (for examples of the datasheets, see appendix A). The Capability datasheets are based on the functional requirements in the DRM/DRA and contain measurable performance metrics. The Technology datasheets address the projected performance requirements and metrics for each technology within the capability. Both datasheets contain information on existing programs, current and projected state-of-the-art values, cost estimates, schedule milestones, and estimates of the degree of difficulty and risk associated with achieving the required degree of maturation. This format also lends itself to peer review that can be effectively used to verify and validate the data.

The Portfolio analysis begins with the technologist providing information on cost, schedule, risk, and projected performance. The projected performance is divided by the state of the art value to achieve a unit-less measure of performance increase. This number is weighted based on the number of missions that will use the technology, and the technologies that comprise a capability are summed in a weighted average based on cost, giving a benefit-cost ratio for each technology and capability. Several budgetary levels are then assumed, and a portfolio analysis is completed at each budgetary level. The algorithm is a simple "grab-bag" type: the highest cost-benefit ratio technology (or capability) that will fit within the remaining budget is chosen. This process is repeated until no technologies (or capabilities) will fit within the remaining budget. Sensitivity analyses are then run, adjusting the cost and the score randomly by a small percentage and recalculating priorities at each budgetary level. These analyses show which

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technologies are on the edge of being included in the portfolio at each budgetary level. The technologies that are not on the edge are the clear winners; the ones on the edge are given estimates of uncertainty based on how often they were excluded from the portfolio at that budgetary level.

The Technology analysis process assesses and prioritizes technologies within a capability based on impact to mission success, programmatic and development risk, and cost related to benefits. The process uses both quantitative and qualitative data to perform an assessment employing a structured hierarchical pair-wise comparison technique utilizing technology and program management expertise.

The results of the Portfolio and Technology analysis form the basis for the investment recommendations. Integrated capability development roadmaps can be developed as a summary graphic of the analysis results.

Iteration of capability assessments to reference missions and architectures:

The feedback from the capability assessment to the mission planners is critical since it will either validate or invalidate the design assumptions. If the capability performance or maturity design assumptions are found to be invalid, a re-planning of the mission and architecture is necessary.

CRAI capability process implementation:

In FY 04 the Exploration Vision had just been announced and no DRM's/DRA's that directly addressed the current vision were available. NASA assembled a "Red/Blue" team to survey the history of Lunar and Mars mission planning and identify common capabilities needed by each case study. The CRAI Team adopted these capabilities as a starting point with the expectation that, since they had been identified in the majority of previous applicable studies, they would be needed for updated missions. The CRAI used DRM's/DRA's that were representative of the previous studies, although in practice they lacked the requisite detail for the full demonstration of the analysis methodologies. While the CRAI capability and technology datasheets represent a good start at collecting the data needed to fully exercise both analytical techniques, there are gaps in the data that fall well short of sufficiency. Cost estimates of capabilities and technology development are particularly suspect and would greatly benefit from independent review. Because of the preliminary nature of the CRAI data, no definitive results are yet possible utilizing the Portfolio and Technology assessment methods. However, sufficient progress was made to determine that the approach and methodology are sound and would fulfill the strategic investment recommendation objectives.

Products:

In FY 04 the CRAI team products included: preliminary assessments of 57 capabilities applicable to the exploration mission, 441 associated technology datasheets, limited

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capability development roadmaps, initial capability and technology databases, and the development of a strategic analysis process that could result in prioritization and optimization of critical NASA capability investments. The 57 capability assessments are documented in the form of White Papers which include: a description of the capability along with its needs and benefits; current and projected state-of-the art (SOA); gaps in the SOA that need to be filled; rough order of magnitude cost and schedule estimates; and, in some cases, technology development roadmaps. For a listing of the capabilities and White Papers see Appendix B.

The CRAI plan also provided for an independent review (also well documented) of the technology assessments using an external team composed of subject matter experts from NASA, industry, and academia. To ensure an independent and impartial assessment, every effort was made to select personnel who were not members of CRAI capability teams or directly involved in the development of the technologies being assessed.

As a related, focused activity, the CRAI team was asked to perform an independent assessment of Automated Rendezvous and Docking (AR&D) capabilities. The primary findings included the need for a program formulation activity and a NASA policy debate and decision on the acceptable level of autonomy for this and other systems. The Exploration Mission Directorate has initiated program formulation based on the specific recommendations in the CRAI AR&D report, thus demonstrating an effective implementation of the 'strategy to tactics' concept. Similar programs could be formulated for other technologies identified by CRAI.

The CRAI plans for FY 05 included: updated and refined functional and performance requirements as NASA released the Exploration mission DRM's/DRA's, further capability and technology database population, data validation and verification, and a more comprehensive strategic investment analysis. In the fall of 2004, however, the CRAI effort was transitioned to the newly formed APIO Roadmap teams. This transition will, at least in the short term, diminish the continuity of the CRAI effort until the APIO team determines the proper disposition of the CRAI data and the appropriate future course of action.

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CRAI Lessons Learned:

1. Guidance from DRM's/DRA's is essential to a structured strategic analysis and credible investment portfolio development.
 - a. These DRM's/DRA's must pay special attention to including specificity with respect to those features that drive the assessment of capabilities and technologies needed to perform them. Input from the technology community is crucial in this regard.
 - b. A feedback mechanism with the mission planners and architects on the results of capability and technology assessments is essential for an informed and integrated design process.
2. High level capability assessments are not meaningful without technical performance measures, cost, likelihood of success and schedule
 - a. Gap analysis between current SOA and needed SOA is dependent on high quality data
 - b. Data collection, while difficult and time consuming, is worth the effort for it leads to an analysis product with integrity based on credibility
 - c. Peer Review of data is essential for credibility. It is necessary to plan for involvement of both external and internal reviewers able to devote the time needed for thorough review.
 - d. Independent cost analysis is needed. For this analysis to be effective, it is required that the basis-for-cost estimates be defined, actively managed, and that assumptions be explicitly stated.
3. The process that leads to the ability to perform a structured strategic analysis that forms the basis for the investment decisions is the most meaningful product of a capability assessment. White papers and Roadmaps are not the exclusive final product; rather they are a summary of the knowledge gained from the analysis process.
4. Capability Management holds promise as a way of implementing the Exploration mission in an integrated, disciplined manner. It also provides visibility into realistic assessments of capability/technology readiness, development costs and schedules, and programmatic risks to overall mission success.
5. Active management and dedicated personnel are needed to implement the process from a One NASA perspective. This is not a trivial undertaking and requires appropriate resources and schedule commensurate with the scope and complexity of the Exploration mission.
6. It is clear that even without a great deal of Exploration mission specificity, there are a number of technologies that are *enabling* critical technologies. In many cases, these technologies are pervasive across multiple capabilities and needed for multiple DRM's/DRA's. Such technologies frequently entail very long periods of

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time to mature adequately. If the time frame discussed in the Exploration Vision still applies, this advancement in many cases must be begin now, even in some cases for critical capabilities not likely required until post 2020, e.g. nuclear thermal propulsion.

7. The Exploration mission will require an Heavy Lift Launch Vehicle (HLLV), possibly human rated and this development, which may not significantly stretch the state of the art, nonetheless will take a long time and require a very large investment. It is clear that the approach to meeting this capability will play a very large role in designing and evaluating candidate DRM's/DRA's. Decisions related to this capability are needed in the very near term.

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CRAI Observations and Recommendations:

In order to achieve the Exploration Program vision, it is imperative that a meaningful process continues for identifying requisite technologies and capabilities and tracking the progress toward making these capabilities available for mission success. In the spirit of support for the future of the program, and in a very real sense, for the future of the Agency, the following is offered:

- 1) The recommended capability roadmap generation and portfolio investment analysis requires:
 - a. Dedicated effort toward definition of Agency plans in the form of one or more DRM's/DRA's and the capability requirements assumed and expressed in the DRM/DRA.
 - b. Access to Agency and external technologist expertise that can dedicate the time needed to fully research and populate the datasheets.
 - c. Continued evolution of Exploration enabling capability and technology data with the requisite level of completeness, documented in an easily used database.
 - d. Independent technical and programmatic review of the data to assure completeness, credibility and integrity of the analysis.
 - e. A structured, analytical process that integrates information across systems such as the Portfolio and Technology assessments.
 - f. Capability assessment feedback to DRM/DRA planners and architects.
- 2) Results from each of the 57 capabilities studied make a case for investment as applicable to the Exploration mission. To invest in fewer, selected capabilities at this point may result in the inability to accomplish key elements of the current Exploration vision. It is anticipated that further mission definition would reveal additional capability development requirements and needs.
- 3) It is necessary to have an formal, authoritative, and visible Exploration leadership function whose role is to generate candidate DRM's/DRA's, receive feasibility feedback from the capability assessment process, and offer NASA and National decision-makers credible, well-documented data from which to make informed decisions.
- 4) It is necessary that a standing organization be established to support Exploration leadership decision making by performing credible capability assessments of the implications of candidate DRM's/DRA's, This includes:
 - a. Assessing the capability feasibility and time required by the various DRM's/DRA's under consideration
 - b. Actively engaging with the DRM/DRA developers to shape their product by ensuring feasibility as well as ensuring that the developers specify those parameters needed to enable the capability assessments

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- 5) If the Exploration Program is to be successful, NASA must adopt an effective template for the management of capability and technology advancement. CRAI introduced the notion of collecting various technologies into a "capability". Understanding the implications of a capability in mission planning directly relates to the quality of the program "formulation" process, and the likelihood of successfully "implementing" the program and achieving the program technical objectives on cost and schedule. This concept provides a natural basis for formulating programs that manage the technology advancement efforts in an effective manner, ensure progress against expectations, and offer investment flexibility as problems arise. A structured formulation process for a program and is needed for capability development and should be immediately initiated by the Agency to determine, in detail as the DRM's/DRA's mature, the appropriate integrated investment strategy.

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Appendix A - Capability Datasheet Example

| Insert Capability Area Here | | | | Mission 1 | | | | | Mission 2 | | | | | Mission 3 |
|-----------------------------|-----------------------------------|-------|-----|--------------------|-------------------------------------|----------------------|---------------------------|---|--------------------|-------------------------------------|----------------------|---------------------------|---|--------------------|
| | | | | FOM | | | | | FOM | | | | | FOM |
| Capability | Brief Description | Units | SOA | minimum acceptable | polarity (what direction is better) | Cost in \$M to TRL 6 | Year capability is needed | Science Achieved | minimum acceptable | polarity (what direction is better) | Cost in \$M to TRL 6 | Year capability is needed | Science Achieved | minimum acceptable |
| Capability 1 - | Description of capability desired | | | | | | 2012 | Description of Science return expected for overall capability | | | | 2012 | Description of Science return expected for overall capability | |
| Sub-Capability 1 - | Metric/ description | unit | | # | +/- | # | 2012 | | # | +/- | # | 2012 | | # |
| | secondary metric for 1.1 | unit | | unknown | +/- | # | 2008 | | unknown | +/- | # | 2008 | | unknown |
| Sub-Capability 2 - | Metric/ description | unit | | # | +/- | # | 2012 | | # | +/- | # | 2012 | | # |
| Sub-Capability 3 - | Metric/ description | unit | | n/a | +/- | # | 2012 | | n/a | +/- | # | 2012 | | n/a |
| Sub-Capability 3 - | Metric/ description | unit | | # | +/- | # | 2012 | | # | +/- | # | 2012 | | # |

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Appendix A - Technology Datasheet Example

| | | | |
|---|--|---|---|
| Contact Information | | | |
| Person Providing Data: | | Secondary Contact: | |
| Phone: | | Phone: | |
| Email Address: | | Email Address: | |
| Capability: | <i>What capability does this technology meet?</i> | | |
| Linkage | <i>To what elements does this technology link?</i> | | |
| Impact Rationale: | <i>How does this technology meet the capability listed</i> | | |
| Technology Name: | | <i>Identifier of technology/program</i> | |
| Description: | | <i>describe the technology or program</i> | |
| Technology Maturity | | | |
| Current TRL (1-6) Time to mature to TRL=6, yrs Total cost to obtain TRL=6 Research Degree of Difficulty (1-5) | | | |
| Dependence on other technologies to meet capability expectations | | | |
| Technologies | Developers | Funded or Unfunded | |
| <i>What technologies does this depend on</i> | <i>Who is developing it?</i> | <i>Yes, No, Partial</i> | |
| Technical Performance Measures | State of Art Value | Projected Value | Probability |
| <i>Power, Mass reduction, etc.</i> | <i>Current SOA value, should be numerical</i> | <i>Projected value at end of technology development</i> | <i>Probability of success if funding is given</i> |
| Technology Development Schedule | | | |
| Year | Milestone | TRL | Cost |
| 11/14 Rev F 11/22/04 | | | |

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Appendix B - Capability and White Paper listing

| Capabilities | White Paper Titles |
|--|--|
| Communications, Computing, and Information Systems | |
| Communications Computing Systems Information Systems | Communication and Networking Infrastructure End-to-End Communications for Space Missions Integrated Systems Health Management Autonomous Operation and Failure Recovery High Efficiency Computing |
| Space Utilities and Power | |
| Power Generation Power regulation and Conversion Energy Storage ISRU Cryogenics Environmental Durability/Survivability | Advanced Power |
| Human Support Systems | |
| Atmospheric Management Advanced Water recovery Systems Waste Management Crop Datasheets Human Factors Advanced Thermal Control Systems Human Support Systems Advanced Environmental Monitoring and Control Advanced Food Technology | Advanced Food Technology Advanced Atmosphere Revitalization Autonomous Medical Care Behavioral Health and Performance Bioregenerative Food Production Environmental Monitoring and Control Human Factors Human Health Countermeasures Radiation Advanced Thermal Control Waste Processing Technology Water Recovery From Wastewater |
| Automation and Robotics | |
| Modeling and Simulation Robotics Surface Operations Subsurface Operations | Intelligence for Robots and Other Complex Systems Robotics |
| In-Space Transportation | |
| OMS RCS Engines Integrated CH4-gO2 RCS Integrated O2-gH2 RCS High Performance LH2-LOX Main Engine Solar Electric Power Nuclear Electric Power Nuclear Thermal Power Precision Entry, Descent, and Landing Long Term Cryogenic Storage Zero-g Fluid Management On-Orbit Cryo Storage and transfer Aero-Capture / Aero-Braking Entry, Descent, and Landing Autonomous Operations Aerodynamics of Non-Traditional Shapes | Cryogenic Oxygen/Methane OMS/RCS Engines (.5-4.5 Kn) Integrated Gaseous Oxygen/Methane RCS System Integrated Gaseous O2/H2 RCS System Hi-Performance LOX-LH2 Main Propulsion Solar Electric Propulsion High Power Nuclear Electric Propulsion Nuclear Thermal Propulsion (NTP) Precision Entry, Descent, and Landing Long Term Cryogen Storage Zero G Fluid Management On-Orbit Cryogenic Fluid Transfer Aerocapture Automated Rendezvous And Docking WP Automated Rendezvous And Docking IA Report Aerodynamics Of Non-Traditional Shapes |
| Scientific Instruments & Sensors | |
| Formation Flying | Formation Flying |

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| | |
|--|--|
| Large Aperture Technology Detector and Instrument Technology | Large Aperture Systems |
| Structures and Materials | |
| Thermal Protection Lightweight, Multifunctional, Integrated Primary Pressurized Structure for Crew Habitation Lightweight Cryogenic Propellant Tanks Radiators Novel Structural Approaches Radiation Protection Advanced Composites Seals and Mechanisms for Dust Control and Long Life Structures for On-Orbit Assembly | Thermal Protection System (TPS) Materials Extremely Lightweight, Integrated Primary Multifunction Structure Lightweight Cryotanks for Propellant Tanks Large Radiators And Associated Thermal Control Radiation Protection Electronics in Space Thermal and Radiation Environments Advanced Material Systems Advanced Seal Development Mitigation of the Effects of Lunar Dust Structures for In-Space Assembly |
| Crew Mobility | |
| Portable Life Support System System Integration Crew Surface Mobility Airlocks | Extravehicular Activity Systems |
| Launch Access | |
| Integrated System Health Management Materials and Structures Navigation, Guidance, and Control Ground Operations | Launch Systems |